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Feature Modeling:
The Incorporation of a Front and Eddy Map into Optimum Interpolation-based Thermal Analyses

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Executive Summary

Ocean acoustics are crucial to modern naval operations. Acoustics constantly change due to the variability in space and in time of the ocean thermal structure. Thus, a thermal analysis system that transforms irregularly sampled data from disparate sources into an analysis of the ocean thermal structure is of increasing importance. In a data-sparse environment such as the ocean, the key to obtaining realistic but cost-effective analyses is the use of all available data sources, as well as the most powerful data assimilation techniques.

Feature modeling is a powerful means of supplementing the limited in situ and remotely sensed data with our understanding of the oceanography of mesoscale ocean features. Initially, the data are used to map the location of mesoscale fronts and eddies. Schematic descriptions of the thermal structure of these features, called feature models, are subsequently used to represent them in the first-guess thermal field. In data-sparse areas, features that would otherwise be poorly resolved in the analysis are instead represented by these schematic models.

The Naval Ocean Research and Development Activity has developed feature models for Gulf Stream front and eddies, as well as an algorithm for the incorporation of the models into the first-guess field. The models were evaluated at the Fleet Numerical Oceanography Center within the Optimum Thermal Interpolation System (OTIS) framework. Subsurface thermal fields constructed via these feature models agree well with observed fields and are substantially more realistic than analyses produced using the current regional operational system, the Expanded Ocean Thermal Structure (EOTS) analysis. Because of the power of feature modeling, it has considerable relevance to other Navy-funded work in ocean modeling and remote sensing.

Acknowledgments

This work was funded by the Space and Naval Warfare Systems Command through the Air-Ocean Prediction Program (Program Element 63207N) and the Satellite Applications and Technology Program (Program Element 63704N). Mr. Mike Clancy of the Fleet Numerical Oceanography Center is thanked for his guidance and discussions. We also thank Dr. John Harding and Mr. Jeff Hawkins for discussions during this project, as well as Ms. Leona Cole and Ms. Charlene Parker for typing the many iterations of this report.

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I. Introduction

Many critical naval operations, such as underwater surveillance, use the acoustics of the ocean environment. Variability in space and in time of the ocean thermal structure can have a profound effect on ocean acoustics. Hence, a thermal analysis system that transforms irregularly sampled data from disparate sources into a real-time, three-dimensional, gridded temperature field (nowcast) for estimating acoustic propagation will be an increasingly important aspect of modern naval operations.

Until recently, the U.S. Navy has used the thermal analysis system known as the Expanded Ocean Thermal Structure (EOTS) system. The Fields-by-Information Blending (FIB) methodology (Holl et al., 1979), which is the basis of EOTS, can directly assimilate gradient information, that is, the location and strength of oceanic fronts. When such information is available, the resulting analysis can reasonably depict the surface expression of mesoscale fronts and eddies. However, a vertical blending process is used to extrapolate the surface anomalies to depth, and the process is not particularly effective. Sharp fronts and mesoscale eddies that actually extend to depths of perhaps 1000 m can lose much or all of their structure below analysis depths of about 100-200 m in an EOTS analysis. Hawkins et al. (1986) have shown that without the gradient information, even the EOTS surface analysis has distorted or missing features. Furthermore, temperature gradients are not directly measured in the ocean and must be estimated from satellite imagery and other data sources.

These problems and other considerations (Williams et al., 1981) have led the Navy's Fleet Numerical Oceanography Center (FNOC), in conjunction with the Naval Ocean Research and Development Activity (NORDA), to develop and test a new thermal analysis system, the Optimum Thermal Interpolation System (OTIS). The optimum interpolation technique is used in OTIS to combine observations with model-predicted and climatological temperature profiles to produce a statistically optimum analysis of the ocean's thermal structure. OTIS is now operational for global-scale analyses (Clancy et al., 1988).

The data sparsity of the ocean, especially at depth, is a serious impediment to making accurate thermal analyses. In a data-rich area, the analysis is strongly influenced by the observations. But, in a data-poor area, the analysis will more closely resemble the first-guess field or the model-predicted field. In OTIS, the first-guess field is a climatology, which has broad, weak gradients rather than sharp, meandering fronts and, of course, all eddies have been averaged out. While this does not present a problem for global-scale analyses, it makes regional analyses, which aspire to analyze the structure of these mesoscale features, more difficult.

Feature modeling gives OTIS the capability to utilize a front and eddy map, thereby augmenting the data available for an analysis. In the feature modeling approach, the surface data are used first to construct a map of front and eddy location. For example, satellite Multichannel Sea Surface Temperature (MCSST) data can be used to locate the surface signature of an eddy. However, there is likely to be little or no subsurface data to describe the eddy. Schematic models that describe the typical three-dimensional structure of the features, called feature models, are then used to represent these features in the first-guess field at the locations indicated on the map. In data-poor areas, the analysis will then resemble these schematic features. A flow diagram of this approach is shown in Figure 1.

The Harvard University Open Ocean Model also uses feature models as a means of overcoming the sparsity of ocean data (Robinson and Walstad, 1987). The model's user determines the location of fronts and eddies from satellite infrared (IR) images and then uses feature models to represent them at those locations. Initialized with these feature models and given the proper boundary conditions, the model can simulate, for example, realistic deep meander formation and eddy cutoff.

The NORDA feature modeling algorithm and test results are described in this report. Chapter 2 discusses some aspects of optimum interpolation. A background discussion of feature models is presented in Chapter 3, and a more specific discussion of the NORDA models is found in Chapter 4. Results shown in Chapter 5

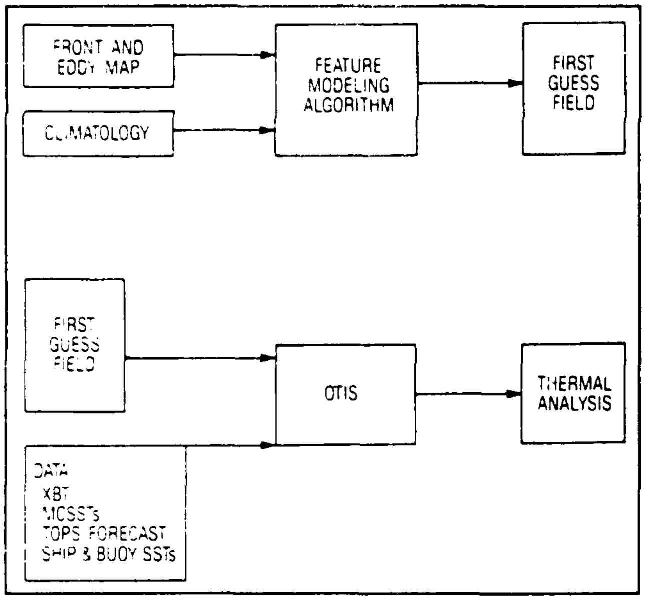

Figure 1. The interface between feature modeling and the OTIS thermal analysis system.

include a test of the eddy feature model, some horizontal and vertical sections through fields constructed via the feature modeling algorithm, and a surface analysis. The relevance of this work to Navy needs and Navy-sponsored ocean sensing and modeling work is discussed in Chapter 6. Chapter 7 has some conclusions and recommendations.

II. Optimum Interpolation

Data assimilation for more effective ocean nowcasts and forecasts should include at least four different but interrelated thrusts. They are (1) the use of more effective data assimilation techniques; (2) the use of model-generated fields as data; (3) the exploitation of new sources of data, such as satellite altimetry and ocean color; and (4) feature modeling, which is the use of schematic representations of fronts and eddies.

These thrusts are embodied in the development of the OTIS system. As explained in the following text, optimum interpolation is a more powerful technique than the FIB method for data assimilation. The numerical weather prediction community, in particular, has effectively used optimum interpolation for many years to assimilate atmospheric data (Carr, 1987; Daly et al., 1985). An example of the second thrust is the use of a Thermodynamic Ocean Prediction System (TOPS) model forecast of the upper ocean as data in a subsequent OTIS thermal analysis. In addition, NORDA anticipates using an ocean circulation model estimate of the depth of the thermocline as supplemental data. Other sources of synthetic data, such as subsurface thermal structure from satellite altimetry, are also being developed. Finally, NORDA, FNOC and the Naval Oceanographic Office (NAVOCEANO) are all active in the application of feature models in optimum-interpolation-based analyses.

Optimum interpolation is a powerful technique for objective analysis and data assimilation. Using the appropriate spatial and temporal correlation scales, optimum interpolation can estimate field values, even in data-sparse areas, by spreading the influence of the available data. The observations can be of disparate types, each with its own characteristic quality (Alaka and Elvander, 1972), thereby readily assimilating new sources of data and model-generated fields. In its general form, optimum interpolation can be applied to scalar, vector or multivariate data sets (Carter and Robinson, 1987). The resulting analysis is the "best" analysis because it minimizes in a least-squares sense the difference between the analysis and an ensemble of observed fields (Bergman, 1978). A particular advantage of the method is that the interpolation error or confidence in the analysis can be explicitly calculated. Optimum interpolation can be used on irregular grids or even at a single point. The formalism for optimum interpolation is given in a number of references (e.g. Bergman, 1978; Lorenc, 1981; Bennett and May, 1987; Clancy et al., 1988) and is not repeated here.

Optimum interpolation was originally applied by Gandin (1963) to the objective analysis of atmospheric pressure and wind data. Although it is now routinely used in numerical weather prediction (Bengtsson, 1975; Lorenc, 1981; Barker et al., 1988), its application to the ocean environment has, until recently, been more limited. Bretherton et al. (1976) and White and Bernstein (1979) have used optimum interpolation for the objective analysis of ocean temperatures, as well as for the design of oceanographic experiments. An extensive ocean description and prediction system, which uses optimum interpolation for data assimilation and objective analysis, has been developed at Harvard University (Robinson and Leslie, 1985; Carter and Robinson, 1987). A general approach, based on optimum interpolation, for estimating the statistics of a random process using finite data, is presented by Bretherton and McWilliams (1980).

NORDA has a broad-based advanced development effort to apply optimum interpolation in support of the operational needs of the U.S. Navy. NORDA has contracted and participated in the development of OTIS (Innis and Williams, 1983; Innis, 1985; Clancy et al., 1988). A higher resolution, surface-only, regional version of OTIS was developed for the assimilation of satellite MCSSTs into a sea surface temperature (SST) map as part of a Space and Naval Warfare Systems Command-funded program known as the Satellite Applications and Techniques (SAAT) program (Phoebus, 1988; 1989). Sampling strategy issues were considered during the Naval Oceanography Program (NOP) funded analysis of the August 1985 airborne

expendable bathythermograph (AXBT) survey of the Gulf Stream by the Regional Energetics Experiment (REX) (Bennett and May, 1987). Currently, work is directed toward the thermal analysis aspect of the Tactical Environmental Support System (TESS) 3.0 (Phoebus and Crout, 1988).

In addition, NORDA has worked in a number of other research areas that are relevant to the use of optimum interpolation. Exploratory development by NORDA is focused on ship-board, optimum-interpolation-based thermal analysis systems (Knauer and May, 1988a,b) and a breadboard ocean forecast system, which couples thermal analysis and prediction with the ocean circulation. This latter project is known as the REX Ocean Prediction Experiment (ROPE), and it emphasizes the assimilation of satellite data, especially altimeter data, into an ocean forecast.

III. Front and Eddy Models

Feature modeling is a means to more fully utilize the limited in situ and remotely sensed data by supplementing the data with our knowledge of the typical structure of fronts and eddies. An extensive discussion of the structure of the Gulf Stream front and eddies is available in the scientific literature and can be used to construct these models. However, significant gaps in our knowledge still exist.

Auer (1987) has made a 5-year climatological survey of the Gulf Stream that produced a number of statistics for the landward edge of the surface front, as well as the warm-core eddies. Hendry (1988) has constructed a parametric model of the Gulf Stream thermal structure. In his model, temperature is specified as a function of pressure and distance normal to the axis of the stream. The purpose of his model is to transform data from moored sensors to a stream-based coordinate system. The theory of frontal dynamics and, in particular, that of the Gulf Stream, has been discussed by Robinson and Niiler (1967), Niiler and Robinson (1967), and Kao (1980). Kao (1980) compared his model to known hydrographic features of the Gulf Stream and found good agreement.

Molinelli and Flanigan (1986) constructed a climatology of Gulf Stream horizontal temperature gradients. They found that the gradients have a Gaussian shape with the parameters given in Table 1 (adapted from Table 6 of Molinelli and Flanigan, 1986). At a 200-m depth, the gradient is centered directly below the northern edge of the ramp in the altimeter signal and is 1.5 ± 1.1 km seaward of the 15°C isotherm. The total temperature change across the front is 9.47 ± 3.45°C. On a grid with a 20-km resolution, which is comparable to the FNOC Gulf Stream grid, they approximate the gradient as 8.1°C across one grid length. The width of the front and the total temperature change increase with depth.

A Gulf Stream eddy, also known as a ring, can be formed when a Gulf Stream meander pinches off. Simple models of eddies have been discussed by Flierl (1979) and Csanady (1979). Observations of eddy structure have been presented by Vastano et al. (1980) and Joyce (1984). Olson et al. (1985) did a case study of the evolution of a warm-core ring, and Flierl and Mied (1985) studied the role of friction in eddy spin-down. Wintertime heat exchange between a warm eddy and the cold atmosphere can substantially cool the eddy, thereby forcing changes in the eddy structure (Dewar, 1986, 1988; Chapman and Nof, 1988).

Table 1. Molinelli and Flanigan (1986) have found that Gulf Stream horizontal temperature gradients have a Gaussian shape of the form $\frac{\partial T}{\partial x} = A1 \exp\left[-\frac{1}{2}\left(\frac{x - A2}{A3}\right)^2\right]$ where T is temperature and x is the lateral distance to the 15°C isotherm at 200 m. The total temperature change, TT, is $TT = \int \frac{\partial T}{\partial x}\,dx$. (Adapted from Table 6 of Molinelli and Flanigan, 1986.)

DEPTH	0 m	200 m	350 m
PARAMETER			
Peak 20-km Gradient $A1$ (°C/km)	0.382 + 0.264	0.404 + 0.199	0.350 + 0.158
Location of Peak $A2$ (km)	-10.68 + 18.36	1.54 + 6.21	8.58 + 9.68
Width of Peak $A3$ (km)	10.14 + 8.94	12.26 + 7.25	16.00 + 6.99
Total Temperature Change TT (°C)	6.76 + 4.62	9.47 + 3.46	11.77 + 4.64

A dynamic or water-mass-based climatology is used in conjunction with feature models. In the traditional or static climatologies, all reasonable temperature profiles within a certain area are averaged to yield a single profile at each location on a regular grid. An example is the U.S. Navy climatology known as the Generalized Digital Environmental Model (GDEM). In a dynamic region such as the Gulf Stream, the data base can include several water masses. Hence, the climatological profile might not resemble any particular water mass. In a dynamic climatology, the data base is sorted by water mass before averaging. The result is a representative profile for each water mass at each grid point affected by that water mass. These water mass profiles can be used to construct the principal water masses associated with a frontal feature model, thereby assuring that the temperature contrast across the frontal model will be realistic. Cummings (1986) constructed temperature fields for the principal water masses in the Northwest Atlantic and applied them to the optimum interpolation of ocean temperatures. Feature models are an important aspect of his method.

The Navy uses satellite imagery and altimetry data along with data from ships of opportunity to construct the weekly front and eddy maps that are used in EOTS and will be used in OTIS. Satellite SST data are the most widespread observations, but they are frequently unavailable in areas of interest due to cloudy conditions. The GEOSAT (Geodetic Satellite) Ocean Applications Program (GOAP) demonstrated the utility of satellite altimetry for locating subsurface front and eddies in the area of strong western boundary currents. Altimetry is particularly useful for locating submerged cold eddies, which have little or no SST signature. It can be used under cloudy conditions but is available only along the nadir track of the altimeter. Satellite SST data are sometimes useful for interpreting the altimetry data.

The front and eddy maps that are received at FNOC can have a number of frontal shingles and spiral arms protruding from the Gulf Stream (see Fig. 2). These shallow features are sometimes formed during the interaction between the stream and a nearby eddy. At depth, the stream follows the path indicated schematically by the dashed line. Hence, the shingles and spiral arms must be edited from the front and eddy map prior to using the map at depth. The approach that is used to edit these features considers the ratio of the straight line distance between frontal points to the distance along the actual path of the front. For example, the distance b-e in Figure 2 is much shorter than the distance b-c-d-e. Therefore, points c and d are assumed to be on a shingle or meander. If the distance b-e is sufficiently small, then the points c and d are assumed to be on a shingle and edited from the map. This simple approach is not fully adequate in cases of very convoluted flow or multiple, closely spaced shingles.

The front and eddy map valid for 28 April-04 May 1988 (Fig. 3), for example, has a number of shingles and spiral arms that need to be edited from the map before it can be used in the feature modeling algorithm. The results of the automated editing of the frontal map are shown in Figure 4. Isolated shingles, such as those labeled a and b on Figure 3, are cut off at the neck in the same way that a human analyst would likely do. The closely spaced shingles and deviations from a straight-line path near the label c are handled less well. The path is straightened but does not necessarily agree with what a human analyst would draw. An unintended

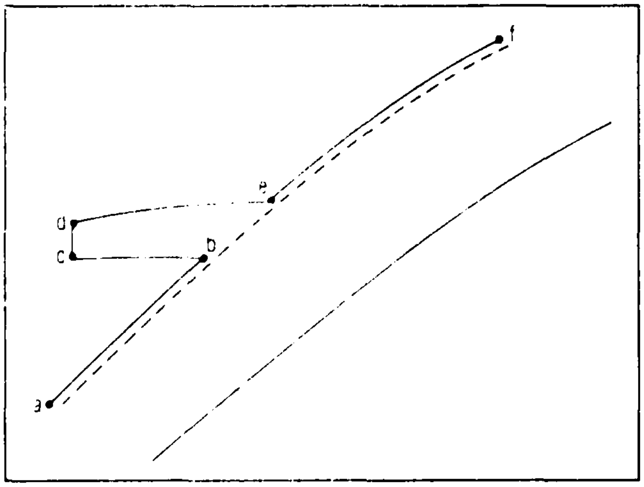

Figure 2. A schematic Gulf Stream frontal shingle. The solid lines indicate the surface position of the north and south walls, while the dashed line indicates the north wall location at depth.

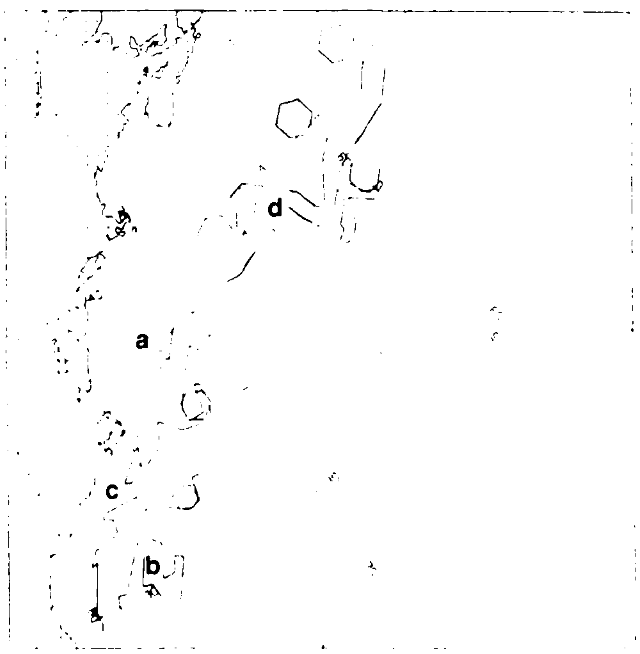

Figure 3. The Navy Gulf Stream front and eddy map valid for 28 April to 4 May 1988.

result is that a meander in the south wall, labeled d, is truncated. The eddies are not involved in the editing process and are simply not drawn in Figure 4.

IV. Technical Description of Feature Modeling

The edited front and eddy map is used to define the principal water masses. A water mass map is built by assigning a water mass type to all of the points in a $0.1^{\circ} \times 0.1^{\circ}$ latitude/longitude grid, which encompasses the analysis area. The position of a point relative to the front is used to assign the water mass type. Each water mass has a distinct integer label and all points in the same water mass have the same label. If both the north and south walls of the Gulf Stream are available, then the water within the stream is identified as a separate water mass.

On either side of the Gulf Stream north wall position, a dynamic climatology is prescribed, while farther from the front, the static GDEM is used. A subjectively located grid index field identifies the analysis nodes where the dynamic climatology is used and those where the static GDEM is used. In the Gulf Stream region, this grid index field identifies a swath through the domain that encompasses the envelope of Gulf Stream frontal meanders. The dynamic climatology is used within this swath and GDEM is used outside it. Since a dynamic climatology has not been implemented at FNOC, each water mass is represented on a monthly basis by a single representative profile obtained from Cummings (1986, NAVOCEANO private communication) rather than by a field.

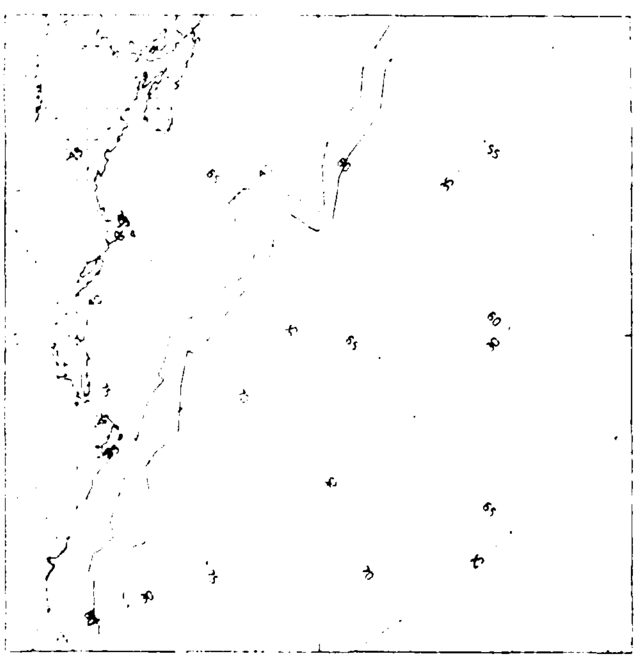

Figure 4. The Navy front map of Figure 3 after the shingles and spiral arms have been edited from the map.

A frontal feature model is now applied to give a more realistic structure to the Gulf Stream front. The north wall on the front and eddy map is the edge between the warm stream water on the right and the negative temperature gradient on the left. The basic approach is to consider a plane orthogonal to the front and to assign temperatures based on depth and on the distance from the midpoint or axis of the front. The slope water mass and Gulf Stream water mass temperatures determine the average temperature, which is assigned to the frontal axis, and the temperature difference across the front. The axis is assumed to slope linearly (0.057 km/m) under the Sargasso water. Below a 900-m depth, the slope of the front is zero. The width of the front is assumed to be 20 km at the surface and increases linearly (0.026 km/m) with depth. A linear temperature gradient across the front is assumed; this assumption is probably adequate at this resolution.

Associated with the Gulf Stream is a flow of warm water in the upper few hundred meters. This water is warmer than both slope water and Sargasso water but cools with distance downstream. The stream temperature is set 1°C warmer than the warmest temperature in the GDEM climatology valid at the date, depth, and longitude of the analysis point. In this way, the temperature of the stream does not deviate too far from climatology.

In order to smooth the boundary between the dynamic climatology and GDEM fields, a filter is applied across the domain, except in the stream water. A result of the filter is to give the Sargasso water, which is initially spatially homogeneous because it is constructed using a single profile, an approximately realistic east-west temperature gradient.

An eddy feature model requires a simple rule that can be used to make a reasonable estimate of the subsurface thermal structure of an eddy from an observed or measured quantity. This model keys on the observation that the depth of the thermocline within a warm (cold) eddy is deeper (more shallow) than its ambient depth, but the thermocline stratification is relatively unchanged. Examples from the literature can be found in Joyce (1984) and Vastano et al. (1980).

In the case of a warm eddy, for example, the typical slope water profile, which describes the ambient water, is shifted downward within the eddy. Sea surface height relative to an assumed level of no motion at 1500 m is used to determine by how much the profile is shifted. When the ambient profile is shifted downward within a warm eddy, relatively cold and fresh water is shifted below the level of no motion. The profile is extended upward to the base of the mixed layer by prescribing a small stable stratification, thereby modeling the 17°C thermostad. The net result is to increase the 0-1500 dB dynamic height. This step is iteratively applied using

small shifts until the surface dynamic height of the shifted profile matches an estimated value, which is described below. This process is shown schematically in Figure 5.

The surface dynamic height can be readily estimated if we assume a schematic but quasi-realistic eddy structure. Based on Joyce (1984), we assume that the eddy core is a disk in solid body rotation that is surrounded by a zone in which the azimuthal velocity decreases linearly to zero. Given the radius of the eddy from the front and eddy map and assuming a typical rate of rotation, the change in surface height across the eddy can be calculated by integrating

$$fv + \frac{v^2}{r} = \frac{\partial h}{\partial r} \quad , \qquad (1)$$

where v is the azimuthal velocity, r is the radial distance, f is the Coriolis parameter, and h is the surface height.

The feature model assumes the eddy mixed layer temperature profile has the same shape as the ambient water but is offset from it. The offset is 1-3°C within the eddy core and decreases to zero within the transition zone surrounding it. A mid-eddy profile is shown in Figure 5, which illustrates the offset.

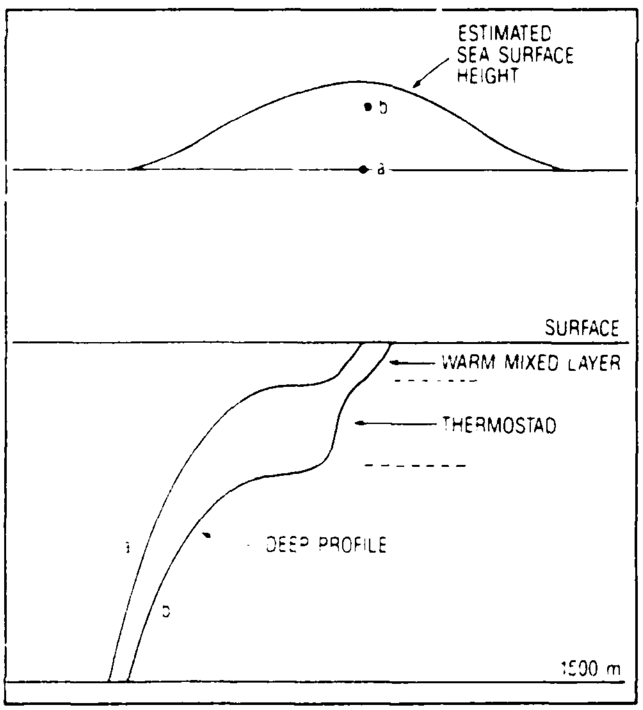

Figure 5. Construction of a warm eddy via a feature model. The ambient slope water has the temperature profile labeled a, which has a surface dynamic height a'. The modeled eddy temperature profile, labeled b, is obtained by shifting and extrapolating the climatological profile a. It is shifted until the modeled surface dynamic height, b', agrees with an estimated sea surface height.

In a cold eddy, a hyperbolic sine curve is used to couple the bottom of the mixed layer to a point just above the main thermocline. As the main thermocline rises within a cold eddy, the thickness of this transition layer decreases, thereby mimicking the packing of isotherms above a cold eddy.

Salinity is important in calculations of dynamic height. Within the core of a warm eddy, for example, the Sargasso temperature-salinity (T-S) relationship is used. The slope water T-S relationship is used outside the eddy. Within the transition region surrounding the core, salinity is interpolated between the core Sargasso value and the ambient slope value. The T-S relationships are approximated from Khedouri et al. (1983) and are given in Table 2.

Once the water masses have been constructed and the front and eddy feature models incorporated, the field is ready to be used as a first-guess field for an optimal-interpolation-based thermal analysis.

V. Results

A. Eddy Feature Model Test

An extensive hydrographic survey of a warm eddy (Joyce, 1984) is used to test the eddy feature model. This data set includes eddy radius and azimuthal speed,

Table 2. Temperature-salinity (T-S) relationships (adapted from Khedouri et al., 1983).

a) Slope — winter		b) Slope — spring	
T	S	T	S
12.0	35.5	15.0	35.0
10.5	35.25	14.5	35.5
6.5	34.9	14.0	35.7
3.0	34.9	13.0	35.6
		4.0	35.0

c) Slope — summer		d) Slope — fall	
T	S	T	S
23.5	34.8	17.0	35.1
23.0	35.1	16.5	35.6
16.0	35.5	12.0	35.7
14.5	35.7	5.0	34.8
14.0	35.7		
5.0	35.0		

e) Sargasso — annual	
T	S
26.5	36.6
20.0	36.6
17.5	36.45
17.4	36.25
16.5	36.1
6.0	35.0

temperature and salinity cross sections down to 4000–5000 m, 100-m currents, and 2000- to 100-dB dynamic height. Using the observed radius and rotation rate, the modeled eddy has a temperature cross section (Fig. 6) that is very similar to the observed section (Fig. 7, Fig. 4a of Joyce, 1984). The eddy is observed to have an SST of 23-24°C, a weak stratification between 17-18°C, and a temperature at the base of the main thermocline of 5-6°C. The gradient at the base of the mixed layer is approximately centered on the 21-22°C isotherms and lies at about 50 m depth. For comparison, the modeled eddy has an SST of 24°C, a weak stratification between 18°C and 19°C, and a temperature at the base of the thermocline of 5-6°C. The gradient below the modeled mixed layer is approximately centered on the 22°C isotherm at about 25-m depth. The modeled isotherm depths are more shallow than observed (Table 3). If a simplified version of the T-S relationship observed by Joyce (1984) is used, then the isotherm depths agree better, indicating some sensitivity to the T-S relationship. Admittedly, opportunities for adjusting the model in this test are more plentiful than in an operational mode. However, these results indicate that this simple, physically plausible method can yield quasi-realistic eddies.

Table 3. Isotherm depths (m) at the center of a warm eddy (a) observed by Joyce (1984), (b) modeled by the feature model using a T-S relationship from Khedouri et al. (1983), and (c) modeled using the T-S relationship observed by Joyce (1984).

	ISOTHERM DEPTH (m)		
	a	b	c
[illegible]	[illegible]	46	50
[illegible]	[illegible]	331	389
[illegible]	[illegible]	398	443
[illegible]	[illegible]	565	595
[illegible]	[illegible]	935	965

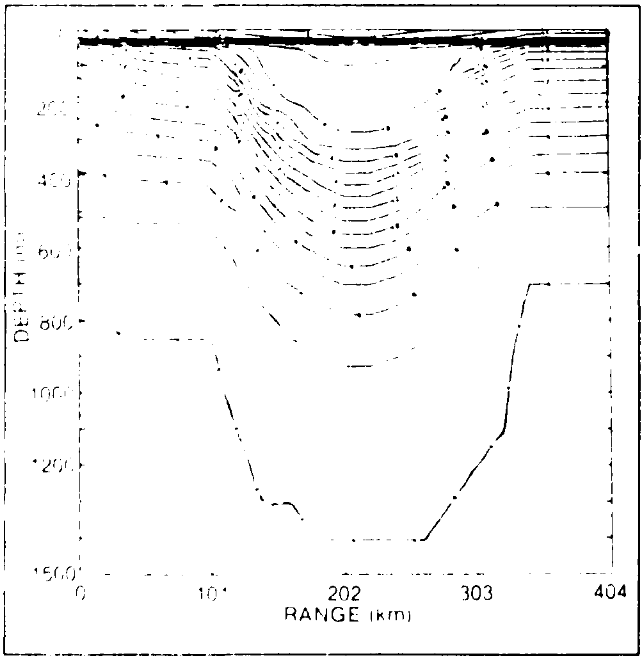

Figure 6. A vertical temperature section through a feature model representation of Gulf Stream warm eddy 81D. This section can be compared to Figure 4 of Joyce (1984).

B. Horizontal Sections

The results of a case study that applies the feature model algorithm to the front and eddy map valid for 10 August 1988 are presented. Quasi-realistic fields are obtained. A comparison with GDEM and the 10 August 1988 EOTS analysis highlights the effectiveness of feature models for describing the oceanic thermal structure.

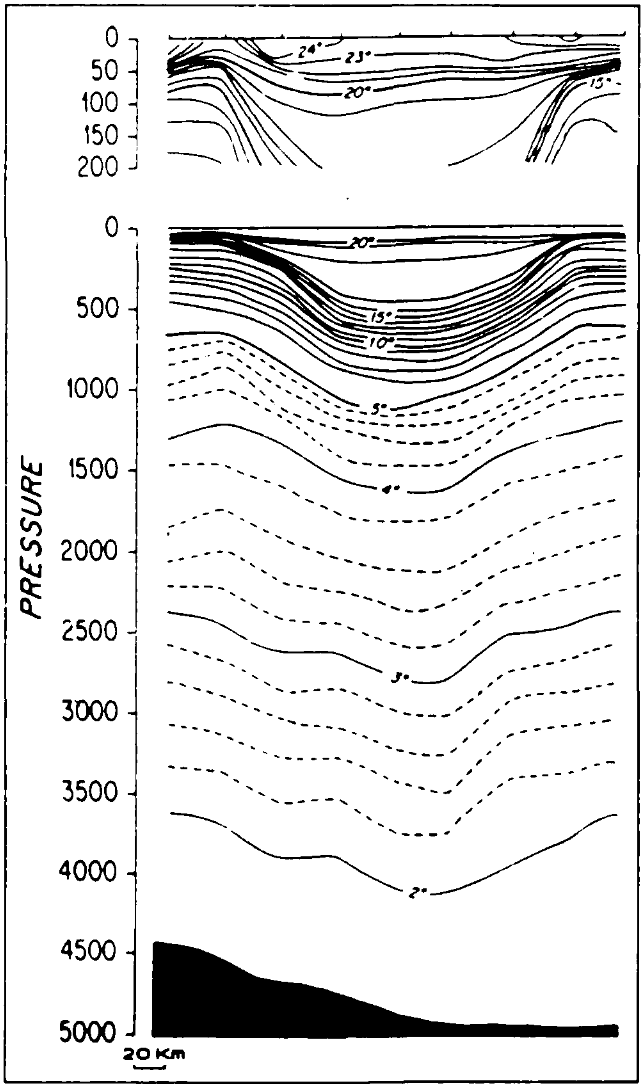

Figure 7. Potential temperature (°C) as a function of pressure (dB) for Gulf Stream warm-core ring 81D. (Figure 4a of Joyce, 1984.)

The construction of a thermal field via feature models begins with the GDEM climatology and a front and eddy map. The GDEM Gulf Stream fields for 10 August at the surface and at 100-, 200- and 400-m depths are presented in Figures 8-11. For later comparisons, the 200-m GDEM field is repeated but with a 3°C contour interval in Figure 12. As noted, GDEM has a broad, relatively uniform gradient from the coast north of Cape Hatteras out to about the seaward edge of the envelope of Gulf Stream frontal meanders (Fig. 1 of Auer, 1987); the Gulf Stream and shelf-slope fronts are smoothed into one broad gradient zone. No mesoscale eddies are present. The front and eddy map valid for 4-10 August 1988 is shown in Figure 13.

Application of the feature modeling algorithm to these fields and map gives the surface field shown in Figure 14. In areas away from the Gulf Stream, the

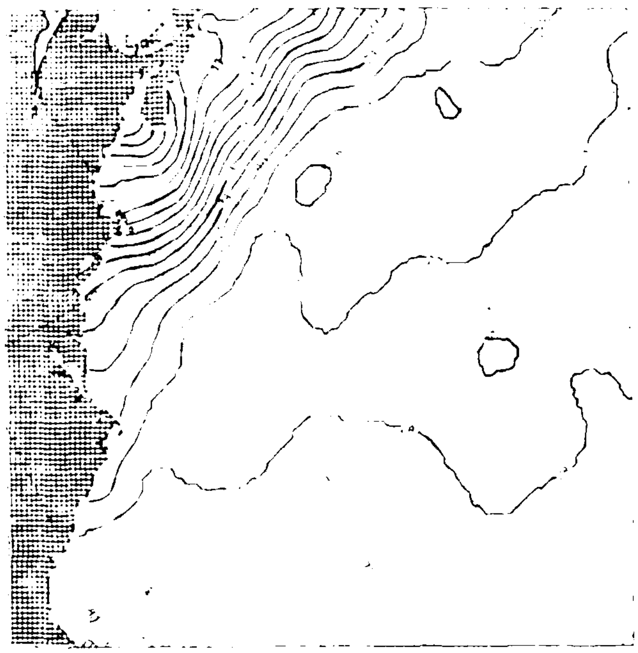

Figure 8. The surface GDEM temperature field for the FNOC Gulf Stream region for 10 August.

Figure 9. The 100-m GDEM temperature field for the FNOC Gulf Stream region valid for 10 August.

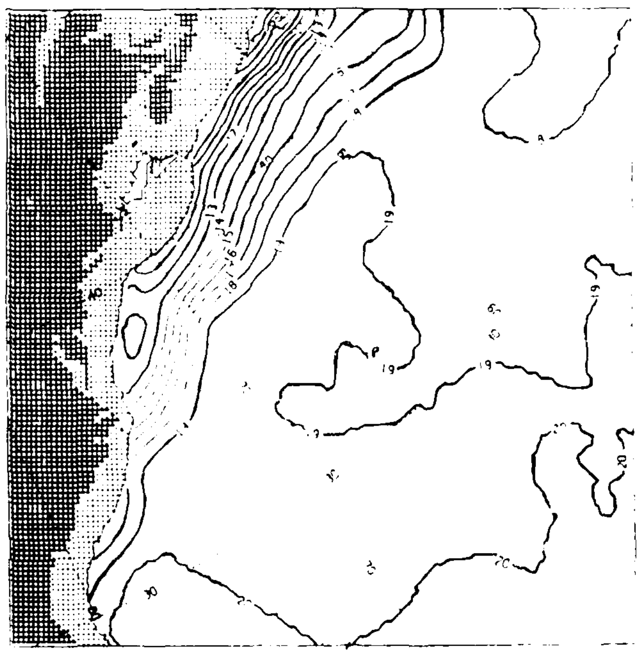

Figure 10. The 200-m GDEM temperature field for the FNOC Gulf Stream region valid for 10 August.

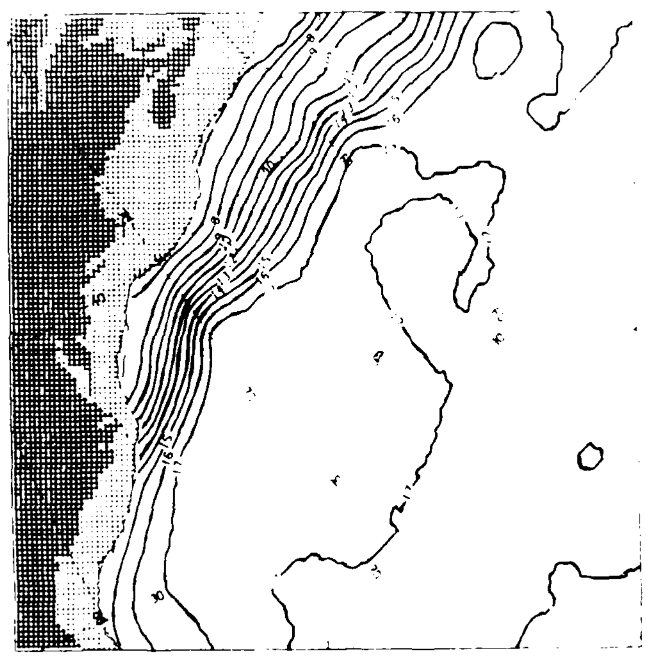

Figure 11. The 400-m GDEM temperature field for the FNOC Gulf Stream region valid for 10 August.

fields resemble the GDEM climatology. See, for example, the Gulf of Maine and the area south of 35°N and east of 70°W. The area just east of the Gulf Stream as it passes the South Atlantic Bight also resembles GDEM. A tight, Gulf Stream north wall front meanders through the domain along the path indicated on the front and eddy map. A weaker south wall front is also evident. Along the shelf break lies a shelf-slope front. Although the surface shelf-slope front can shift seaward all the way to the Gulf Stream, its position is fixed at the shelf break in the present algorithm. The temperature of the stream is approximately 1°C warmer than the maximum GDEM temperature in that vicinity. For example, the stream has a temperature of about 28°C near 70°W, while GDEM has a maximum temperature of 27°C in that vicinity. In addition, we find an eddy at each location indicated on the front and eddy map. The change in SST across an eddy, which is about 2°C, is concentrated near the edge of the eddy.

The fields have similar characteristics at depth (Figs. 15-17). Away from the front, the temperatures are similar to the GDEM values. The north wall front remains tight at depth but broadens somewhat and tilts under the warm Sargasso water as depth increases. The south wall is not evident at 400-m depth. The Gulf Stream front continues south of Cape Hatteras, although it is occasionally interrupted by the bottom. The base of the shelf-slope front is observed to be anchored on the shelf break; no shelf-slope front is seen in the 400-m feature-modeled field.

The eddies are clearly evident at depth. Again, the temperature gradient is concentrated near the edge of the eddies. Larger eddies have a stronger temperature gradient because, at a constant rate of rotation, larger (feature model) eddies have greater changes in sea surface height and, hence, greater shifts of the representative temperature profile. Cold eddies, which are sometimes observed to have no SST signature, become stronger at greater depths than do the warm eddies.

Figure 12. The 200-m GDEM temperature field for the FNOC Gulf Stream region valid for 10 August contoured with a 3°C contour interval.

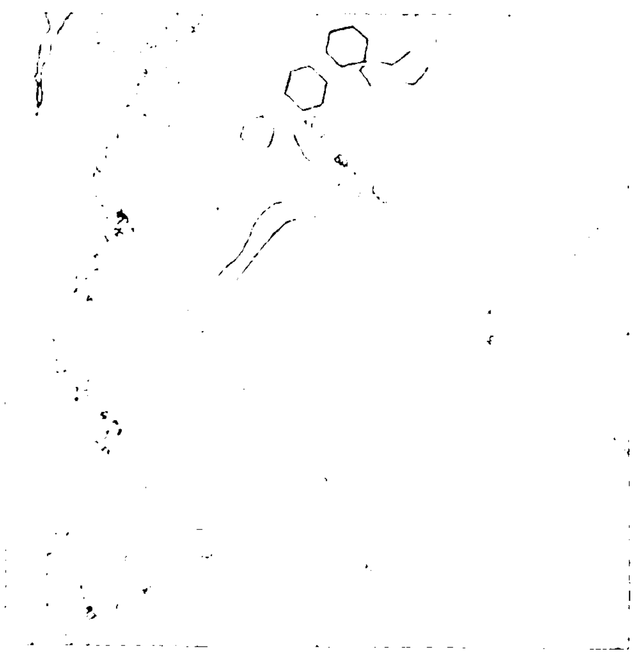

Figure 13. The Navy Gulf Stream front and eddy map valid for 5-11 August 1988.

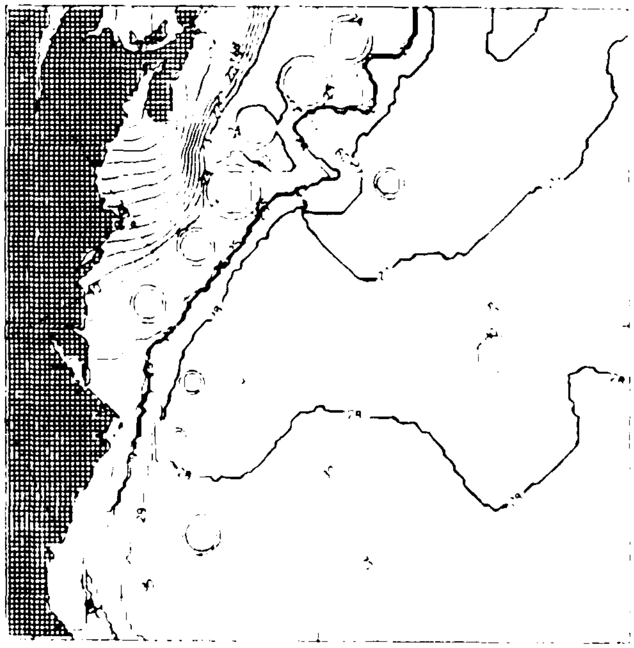

Figure 14. The surface feature modeled field for the FNOC Gulf Stream region valid for 10 August 1988.

The 200-m field is shown again in Figure 18 but with a 3°C contour interval. The narrow meandering front is still evident and agrees with the observation that the 15°C isotherm is the axis of the Gulf Stream front at 200 m. Also clearly seen are the eddies. This contour interval emphasizes that large, warm eddies have stronger gradients associated with them than do small, warm eddies.

For comparison, the 10 August 1988 EOTS analyses at the surface and at 100-, 200-, and 400-m depths are shown in Figures 19-22. Note that these EOTS analyses have BT and other data blended into them. Recall that

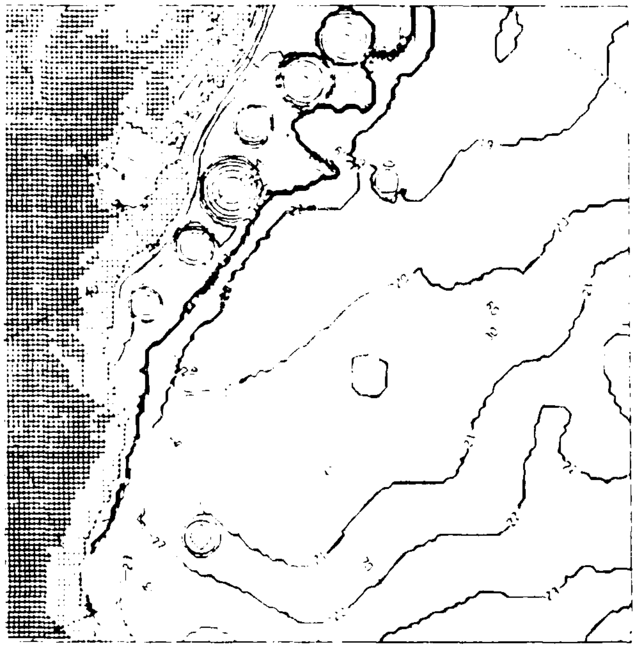

Figure 15. The 100-m, feature-modeled temperature field for the FNOC Gulf Stream region valid for 10 August 1988.

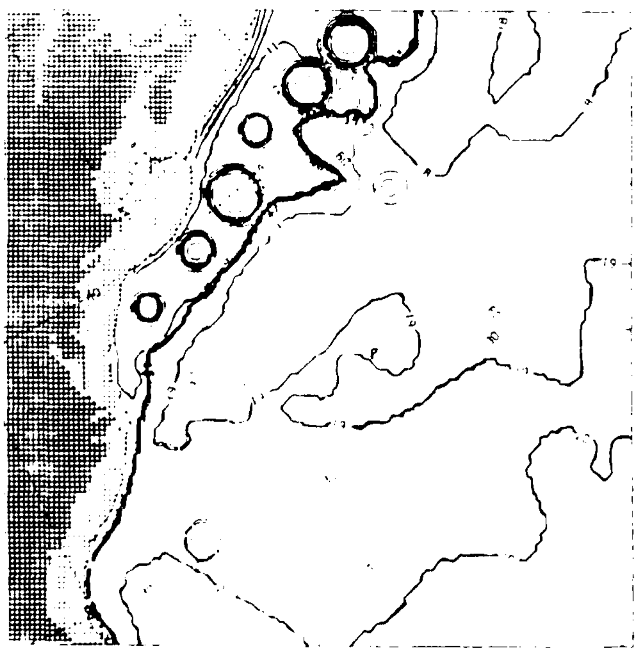

Figure 16. The 200-m, feature-modeled temperature field for the FNOC Gulf Stream region valid for 10 August 1988.

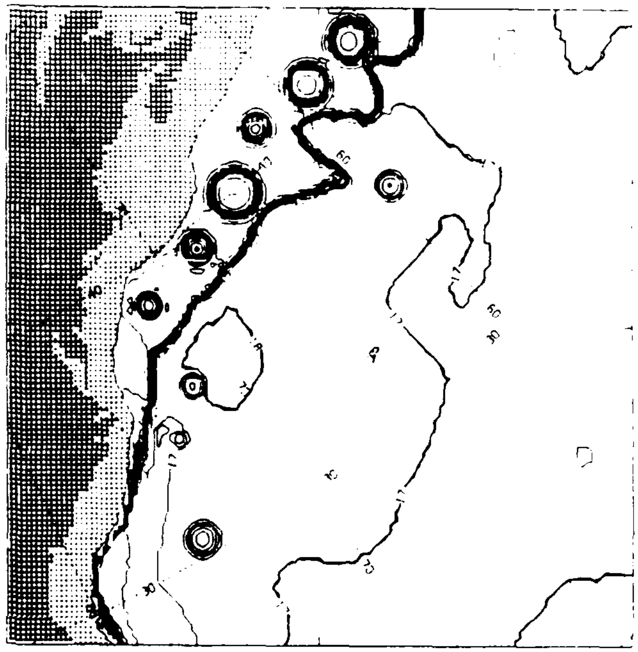

Figure 17. The 400-m, feature-modeled temperature field for the FNOC Gulf Stream region valid for 10 August 1988.

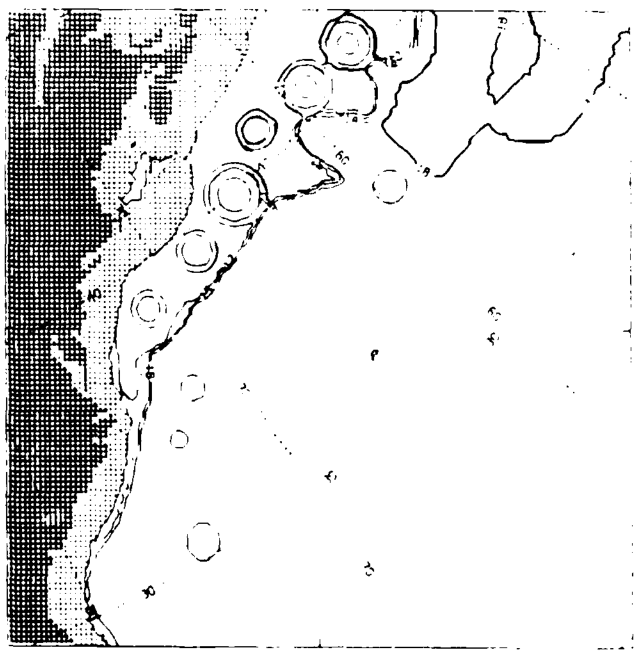

Figure 18. The 200-m, feature-modeled temperature field for the FNOC Gulf Stream region valid for 10 August 1988 contoured with a 3°C contour interval.

EOTS uses the front and eddy map and associated gradients at the surface along with a vertical blending process. Hence, the eddies and the tight, meandering front are evident at the surface at the proper locations. However, the eddies are much less evident at 100-m depth and are missing at still greater depths. The exception is the warm eddy near 40°N, 55°W, but even it is considerably weaker than the corresponding feature model eddy. As depth increases, the front broadens considerably and loses its meanders until it becomes nearly zonal. The 200-m EOTS analysis is repeated in Figure 23 but with a 3°C contour interval. Note the wide separations between the 15°C and the 18°C isotherms, as well as the lack of eddies. The front is poorly described south of Cape Hatteras.

The 200-m EOTS analysis (Fig. 23) resembles GDEM (Fig. 12) more than it resembles the feature-modeled field (Fig. 18). The observation concerning the

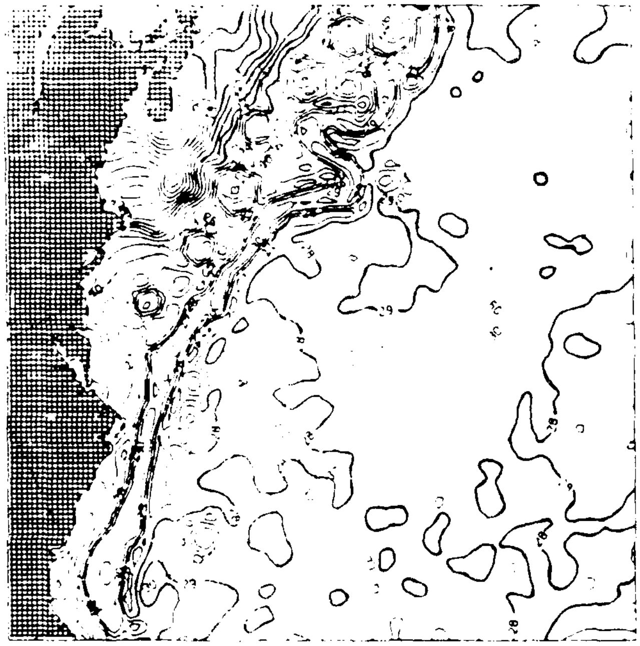

Figure 19. The surface EOTS thermal analysis for the FNOC Gulf Stream region valid for 10 August 1988.

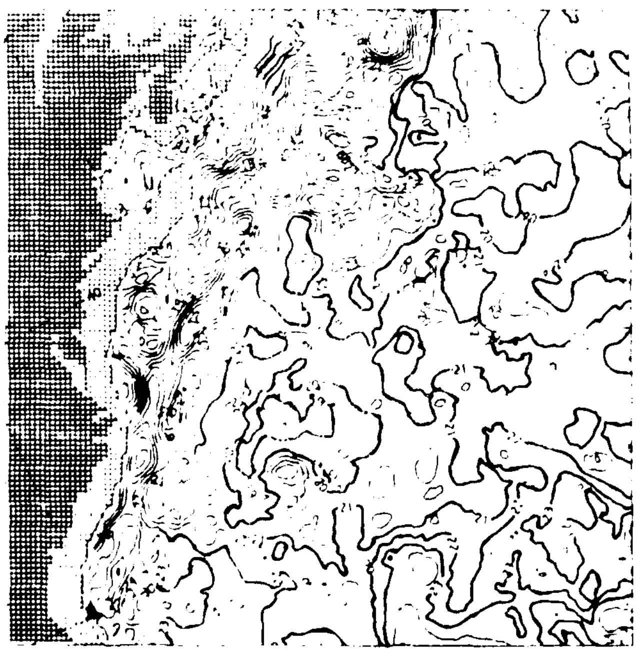

Figure 20. The 100-m EOTS thermal analysis for the FNOC Gulf Stream region valid for 10 August 1988.

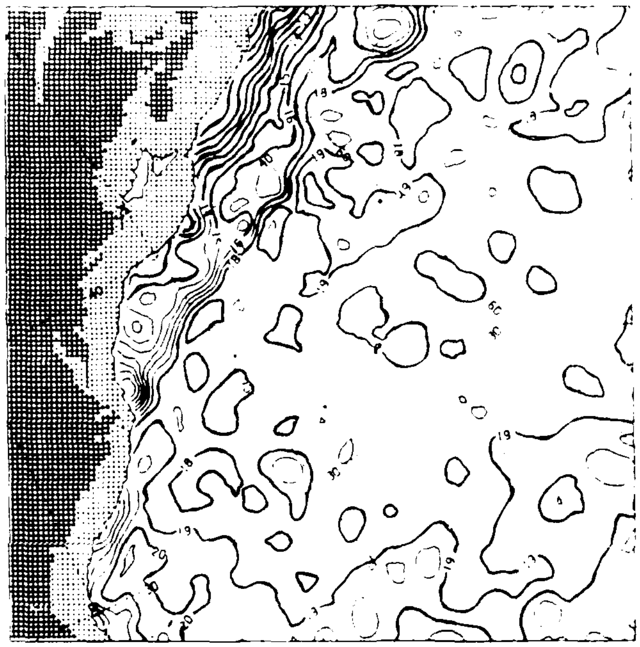

Figure 21. The 200-m EOTS thermal analysis for the FNOC Gulf Stream region valid for 10 August 1988.

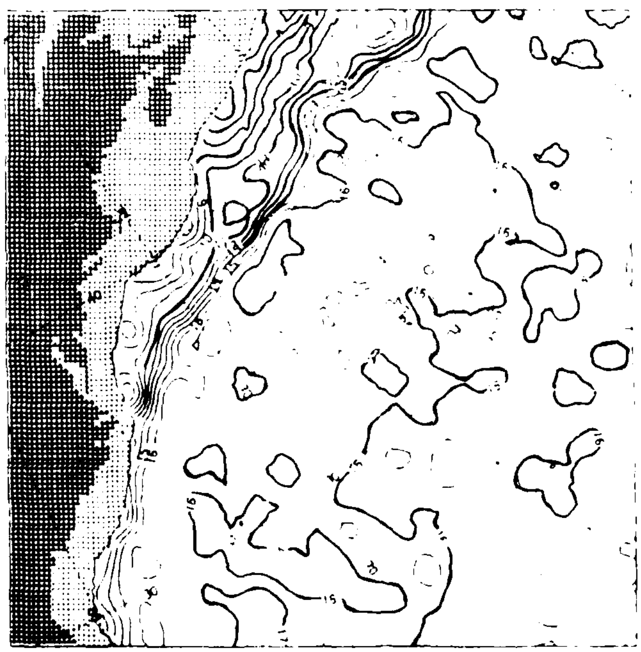

Figure 22. The 400-m EOTS thermal analysis for the FNOC Gulf Stream region valid for 10 August 1988.

15°C 200-m isotherm is not satisfied by EOTS. The unrealistic structure in EOTS results from the lack of subsurface data and the ineffectiveness of the vertical blending. Although the feature-modeled field has no data other than the locations of the front and eddies, it has quasi-realistic thermal structure. This comparison highlights how effective feature models are for describing the thermal field in data-sparse areas.

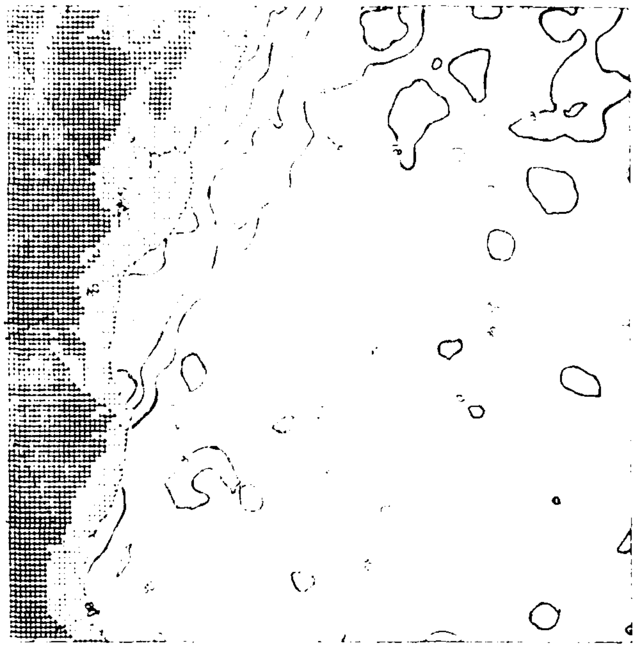

Figure 23. The 200-m EOTS thermal analysis for the FNOC Gulf Stream region valid for 10 August 1988 contoured with a 3°C contour interval.

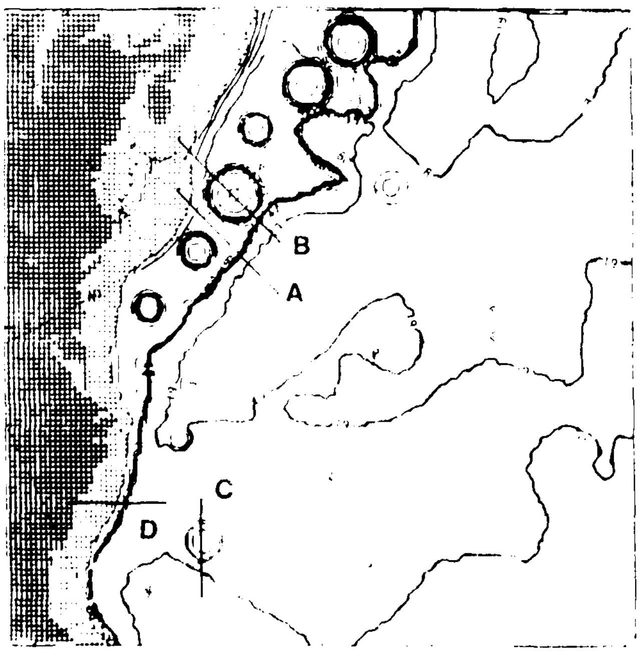

Figure 24. A map of location and the labels of several vertical cross sections through the feature modeled temperature field.

C. Vertical Sections

A series of vertical cross sections through the 10 August 1988 feature-modeled field are presented to

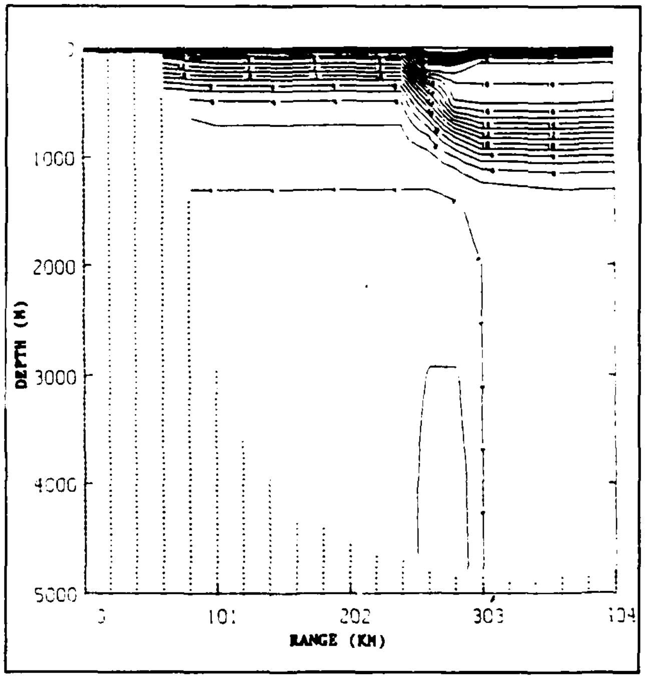

Figure 25. A 0- to 5000-m vertical temperature cross section through the feature-modeled field along track A in Figure 24. North is to the left. Bottom topography is depicted by the vertical columns of +.

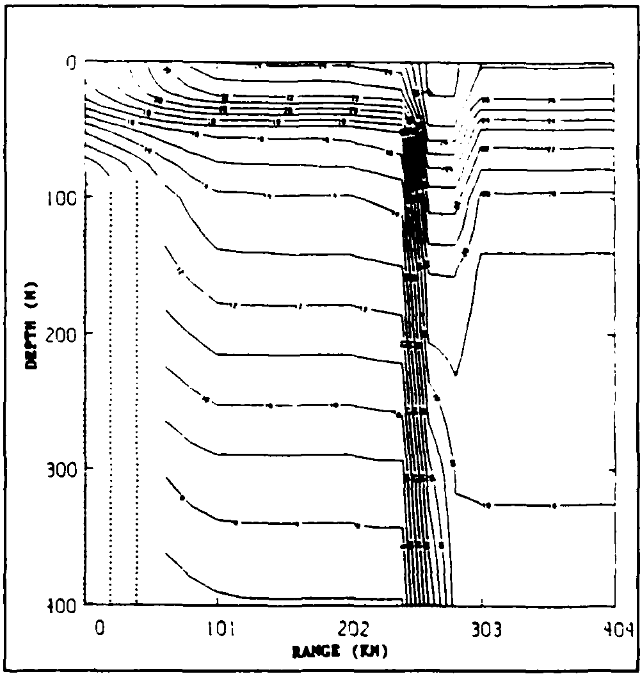

Figure 26. A 0- to 400-m vertical temperature cross section through the feature-modeled field along track A in Figure 24. North is to the left. Bottom topography is depicted by the vertical columns of +.

show the vertical structure of this field. The locations and labels of these sections are shown in Figure 24.

Section A crosses the Gulf Stream near 66.5°W at near-normal incidence. The 0- to 5000-m (Fig. 25) and 0- to 400-m (Fig. 26) sections can be compared to sections in the literature, such as one near 69°W (Fig. 27, Fig. 7 of Watts, 1983) and another near 73°W (Fig. 28, Fig. 10 of Halkin and Rossby, 1985). The feature-modeled and observed water masses juxtaposed across the front have similar characteristics. Compare, for example, the Sargasso 1000-m temperatures and the weak stratification near the 17-19°C isotherms. On the slope water side, the depths of the 5°C and 10°C isotherms approximately agree. All three sections have a surface flow of warm stream water, although the feature model perhaps extends it to greater depths.

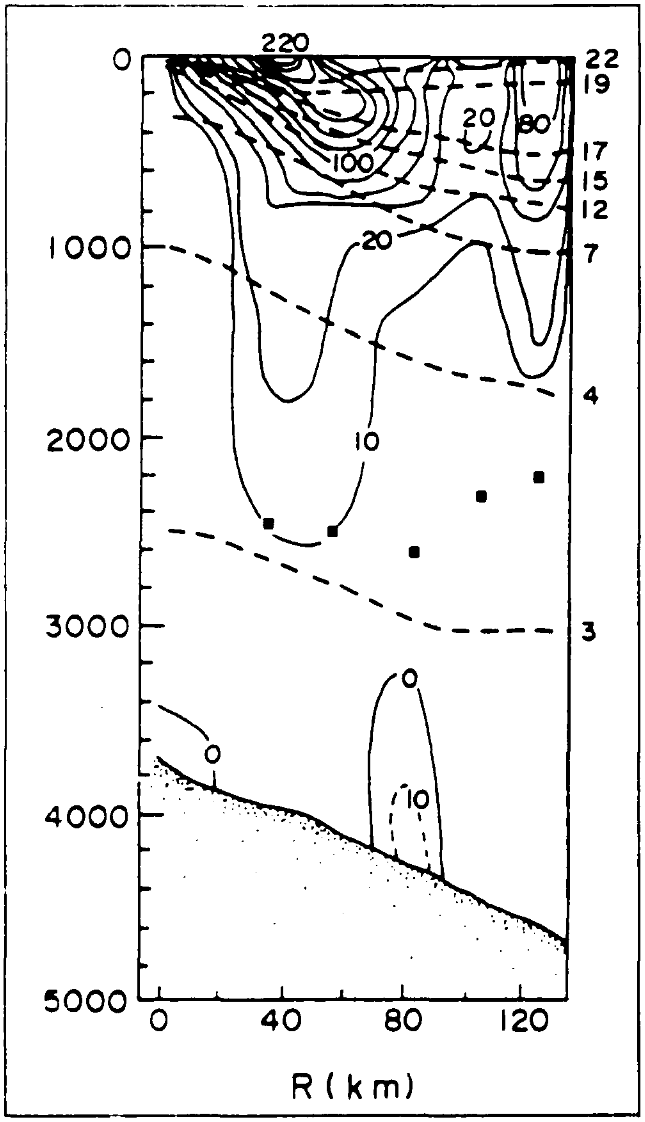

Figure 27. A Gulf Stream section near 69°W showing isotachs (cm/s, solid lines), isotherms (°C, dashed lines), and the position of Swallow floats (solid squares). (Figure 7 of Watts, 1983.)

Section A can also be compared to the results of Molinelli and Flanigan (1986). Table 1, which is adapted from Table 6 of Molinelli and Flanigan (1986), summarizes some of their results. Above 200 m, the feature model section does not have any tilt with depth because the grid resolution is approximately the width of the front. Between 200 m and 350 m, the width of the front approximately doubles from 1 grid interval to 2 intervals. The total temperature changes across the front at 0 m, 200 m, and 350 m are, respectively, about 4°C, 7°C, and 9°C. The 200-m front is closely centered on the 15°C isotherm. The model results agree well with the Molinelli and Flanigan results.

Section B (Figs. 29 and 30) begins on the continental shelf, bisects a warm eddy, and then crosses the front at near-normal incidence. It resembles an AXBT section taken by the REX program (Fig. 2 of Bennett and May, 1988). Section C (Fig. 31) bisects a cold eddy. Finally, Section D (Fig. 32) crosses the front as it lies just off the continental shelf break. Note that the isotherms approximately parallel the sloping bottom. Blanton et al. (1981) show sections in which the isotherms similarly parallel the sloping bottom (Fig. 33, Fig. 4 of Blanton et al., 1981).

D. Surface Analysis

A thermal analysis that blends observational data into a feature-modeled first-guess field has been made using the optimal-interpolation-based software developed by the SAAT program. The spatial distribution of MCSST (Fig. 34) and ship (Fig. 35) observations for 28 March–30 March 1988 are shown. Note that the MCSST data are clustered, leaving large areas with no MCSST observations. The ship data are more uniformly distributed but are of coarser resolution and poorer quality than the MCSSTs.

The March GDEM surface climatology is shown in Figure 36. When the data are incorporated into this first-guess field using optimum interpolation, the analysis (Fig. 37) has a tight front in the MCSST-rich swath east of Cape Hatteras and Chesapeake Bay but a climatological gradient in other, data-poor areas.

A feature-modeled first-guess field is shown in Figure 38. Note the tight front meandering across the width of the domain. The analysis (Fig. 39) made from this first-guess field has a quasi-realistic front almost everywhere. The front is somewhat broad just east of Cape Hatteras because the feature model front was not properly located, possibly because of an aged front and eddy map (Phoebus, 1989). Near 69°W, at the edge of the MCSST-rich data swath, the front is almost discontinuous. Also, the cold eddy near 37°N, 58°W is absent from the analysis that uses climatology alone as a first-guess field, but exists in the feature-modeled analysis. In general, the feature-model-based analysis is considerably more realistic than the analysis based on climatology alone as a first-guess field.

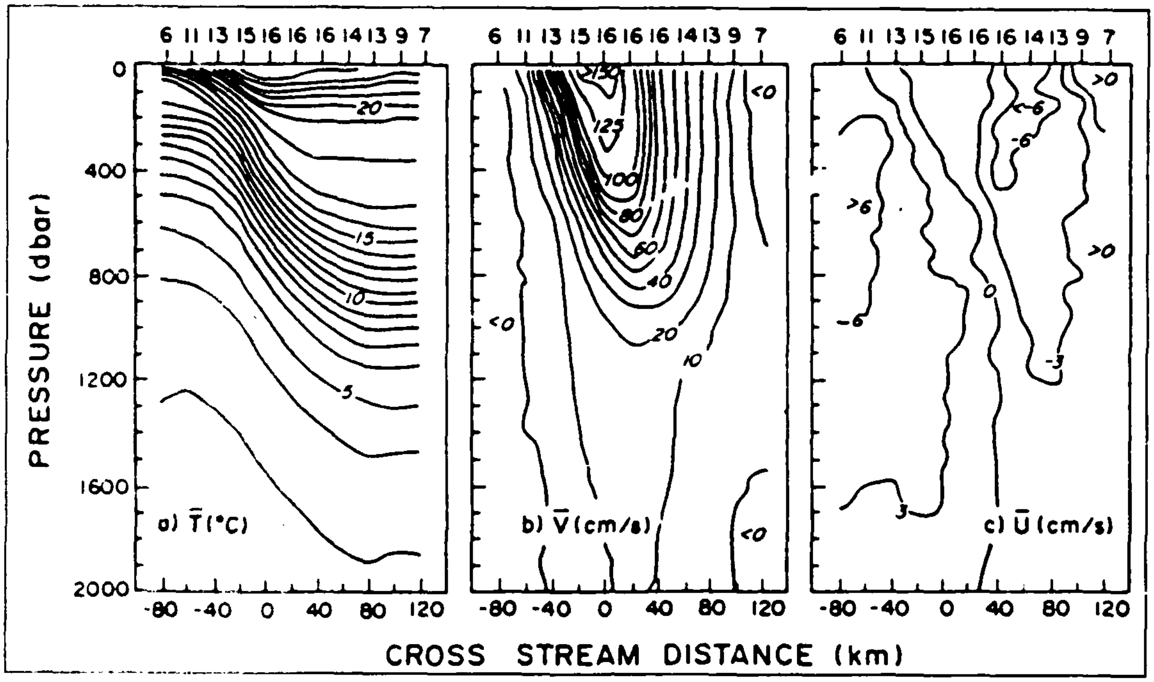

Figure 28. Average Gulf Stream temperature ($\bar{T}$), downstream velocity ($\bar{U}$), and cross-stream velocity ($\bar{V}$) in the "stream" coordinate system. The "stream" coordinate system has axes along the flow of the stream and perpendicular to it. (Fig. 10 of Halkin and Rossby, 1985.)

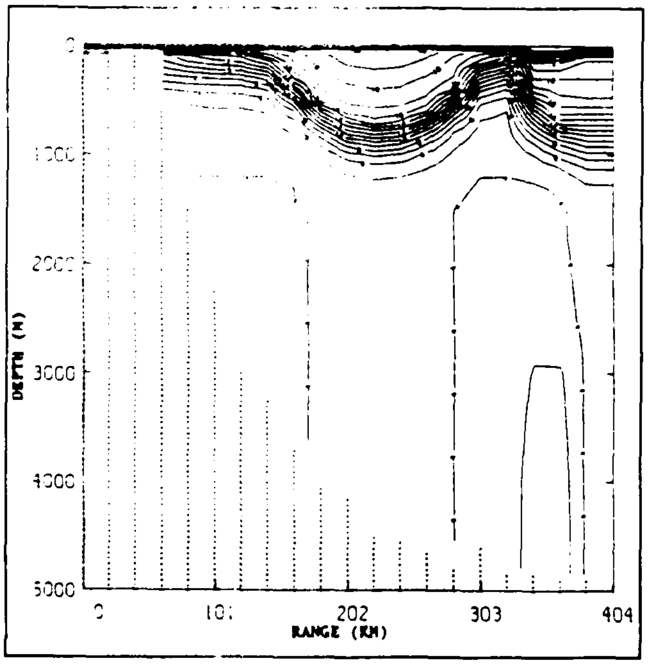

Figure 29. A 0- to 5000-m vertical temperature cross section through the feature-modeled field along track B in Figure 24. North is to the left. Bottom topography is depicted by the vertical columns of +.

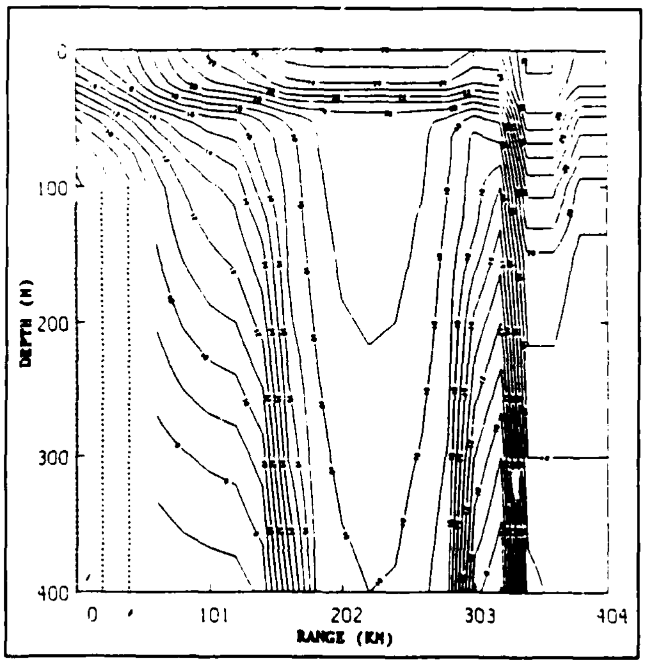

Figure 30. A 0- to 400-m vertical temperature cross section through the feature-modeled field along track B in Figure 24. North is to the left. Bottom topography is depicted by the vertical columns of +.

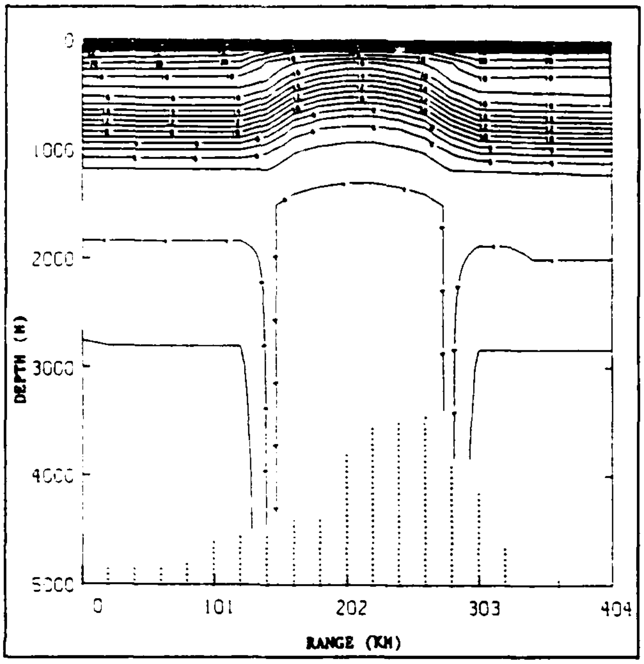

Figure 31. A 0- to 5000-m vertical temperature cross section through the feature-modeled field along track C in Figure 24. Southwest is to the left. Bottom topography is depicted by the vertical columns of +.

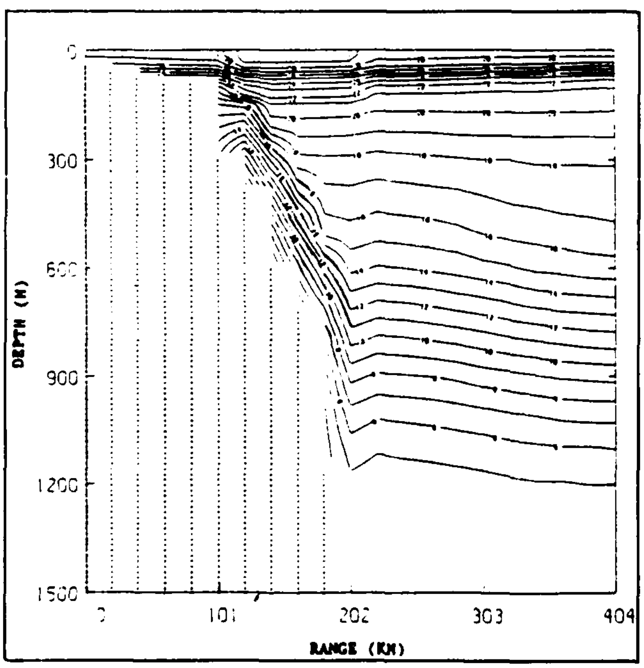

Figure 32. A 0- to 1500-m vertical temperature cross section through the feature-modeled field along track D in Figure 24. Northwest is to the left. Bottom topography is depicted by the vertical columns of +.

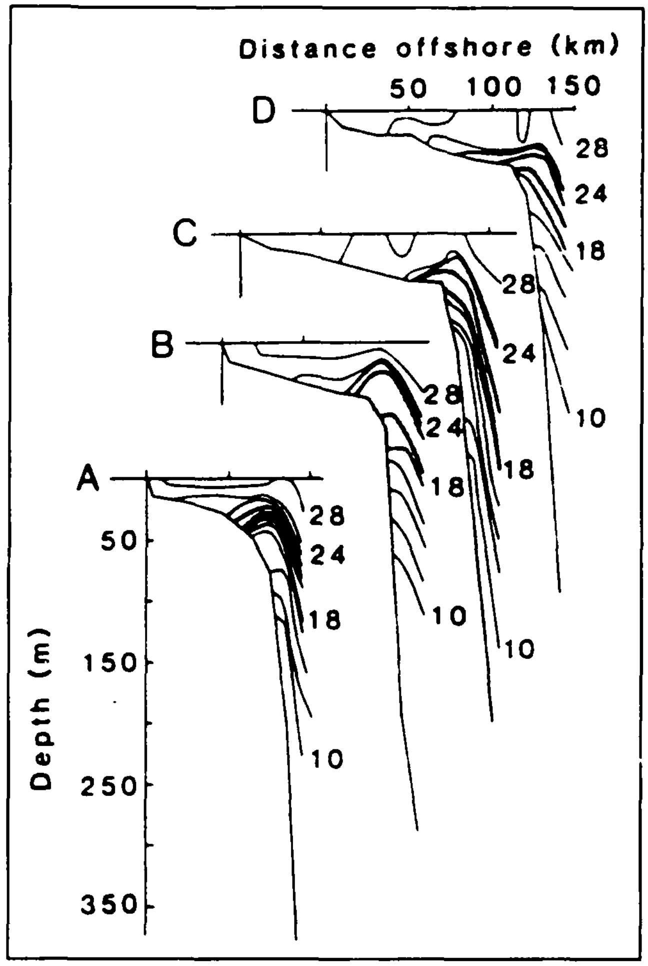

Figure 33. Temperature (°C) transects across the continental shelf between Cape Hatteras and Cape Canaveral. These sections are located off of (a) New Smyrna Beach, (b) St. Augustine, (c) Brunswick, and (d) Savannah. (Fig. 4 of Blanton et al., 1981.)

Figure 34. The spatial distribution of 12439 MCSST observations for the FNOC Gulf Stream region between 00Z 28 March 1988 and 12Z 30 March 1988.

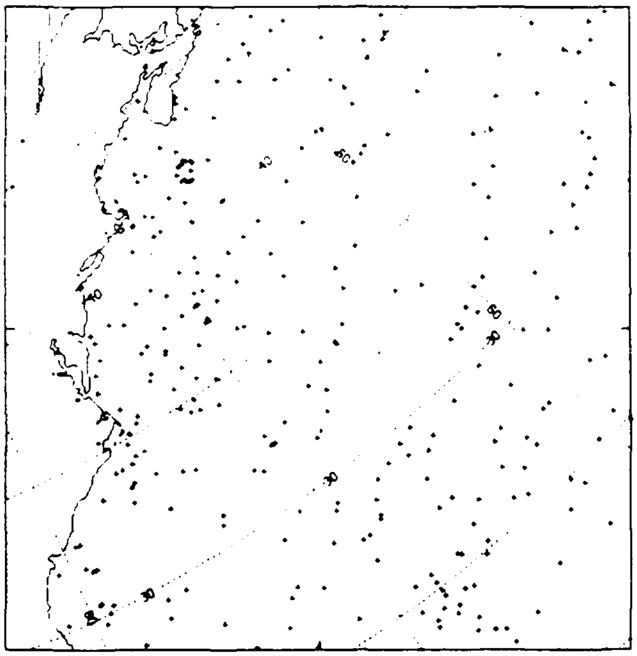

Figure 35. The spatial distribution of 1028 ship-observed SSTs for the FNOC Gulf Stream region between 12Z 28 March 1988 and 12Z 30 March 1988.

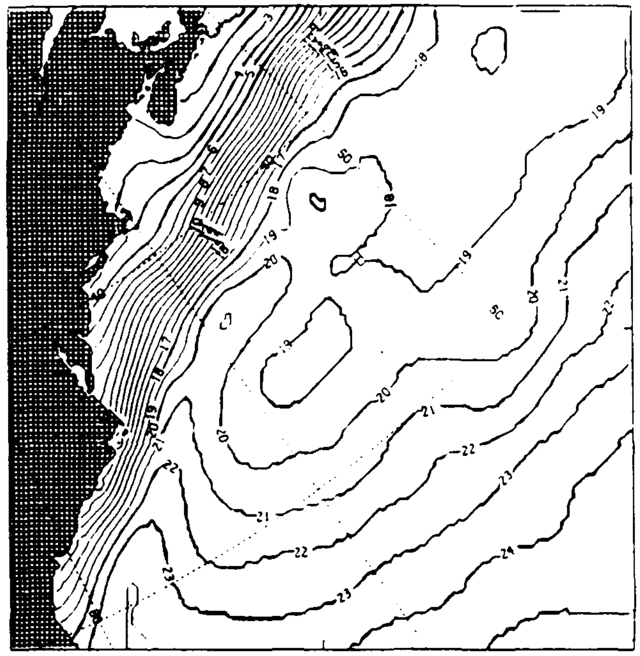

Figure 36. The surface GDEM temperature field for the FNOC Gulf Stream region valid for 30 March.

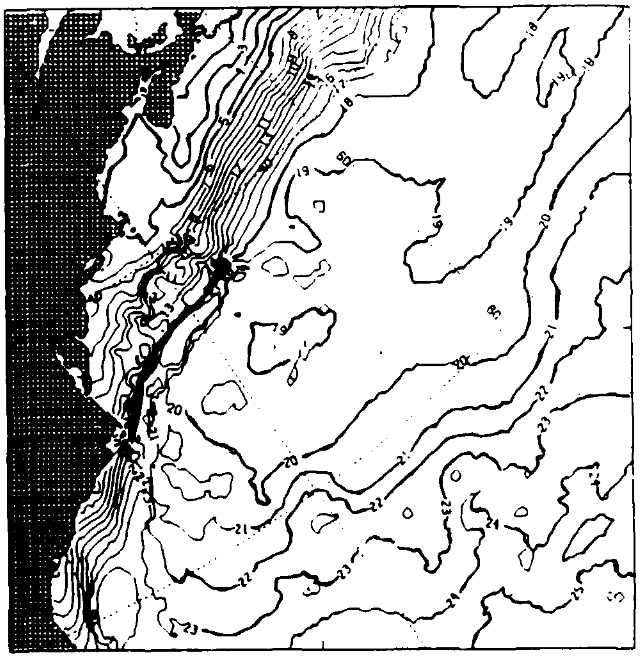

Figure 37. A surface thermal analysis obtained by blending MCSST (Fig. 34) and ship (Fig. 35) data into the GDEM climatology (Fig. 36) by means of optimum interpolation.

VI. Discussion

Feature-model-based thermal analyses can better contribute to meeting the operational needs of the U.S. Navy. Fronts and eddies are acoustically important features. Feature models are a means for incorporating into an analysis a feature whose position has been identified but for which there are little or no in situ data. An example would be a submerged cold eddy that has been located using satellite altimetry but has not been sampled with BTs. Acoustic propagation can now be estimated using a more realistic and complete thermal analysis.

Feature modeling will likely improve the initialization of other Navy ocean models. The analysis that initializes the 1- to 3-day, mixed-layer thermal forecasts will have a more complete and realistic representation of the fronts and eddies in the horizontal but perhaps little new information on the important stratification within the mixed layer. Feature model products should be particularly useful for initializing circulation models that have only a few layers. These models require high horizontal resolution but need only coarse vertical resolution. The NORDA ROPE project is investigating the initialization of a two-layer, primitive equation circulation model for the Gulf Stream region using a surface dynamic height field calculated from a feature-model-based thermal analysis. The preliminary results are promising. Until now, operational Navy thermal analyses have been unsatisfactory for initializing ocean circulation models because of the weak subsurface fronts in the analyses.

Feature modeling provides an additional means of incorporating satellite data into a thermal analysis and ultimately into ocean thermal and circulation forecasts (Fig. 1). Satellite-derived sea surface temperature data have been directly incorporated into surface thermal analyses for some time. A key aspect of feature modeling is the construction of a front and eddy map from all available data including, in particular, IR satellite images and altimetry data, which cannot be directly assimilated into a thermal analysis. Through the use of feature models, fronts and eddies identified in the remotely sensed data can impact the analysis at all levels, both surface and subsurface.

New technologies can also improve the front and eddy maps. The all-weather but relatively low-resolution mapping of strong boundary currents using SST data from the Low Frequency Microwave Radiometer, once proposed for the now-defunct Navy Remote Sensing System satellite, would be an improvement over persistence during sustained, cloudy conditions. Satellite-derived ocean color data might be useful for mapping fronts, eddies, and areas of upwelling. The spiral path of a drifting buoy that is embedded in an eddy can be used to infer the position, translation speed, and rotation rate of the eddy (C. Horton, NAVOCEANO, private communication). Ultimately, front and eddy positions might be obtained from a circulation model that assimilates these and other types of data.

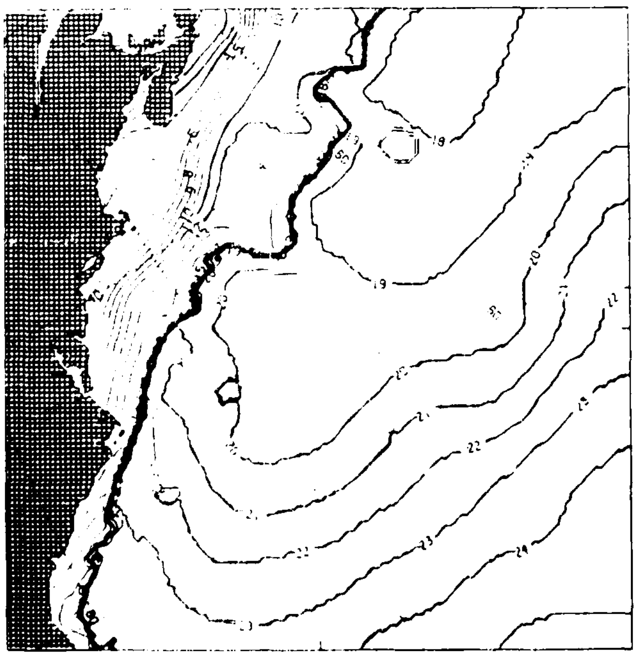

Figure 38. The surface-feature-modeled temperature field for the FNOC Gulf Stream region valid for 30 March 1988.

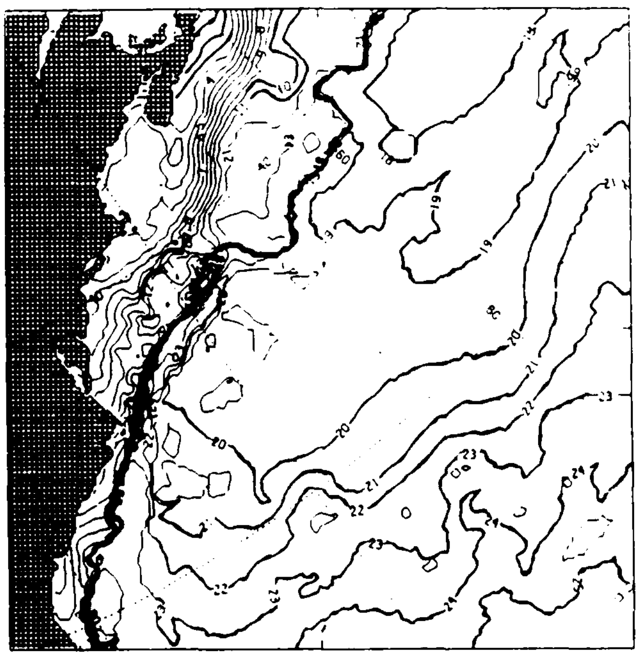

Figure 39. A surface thermal analysis obtained by blending MCSST (Fig. 34) and ship (Fig. 35) data into the feature-modeled, first-guess field (Fig. 38) by means of optimum interpolation.

VII. Conclusions and Recommendations

Feature modeling is the incorporation of schematic descriptions of the thermal structure of fronts and eddies into an ocean nowcast. These schematic descriptions are known as feature models. The conclusions of this report are that (1) a feature-modeled first-guess field is considerably more realistic than climatology alone because it has a tight thermal gradient meandering along the identified frontal path and a quasi-realistic eddy at each identified eddy location; (2) a thermal analysis can have a tight frontal gradient meandering across the analysis domain and quasi-realistic eddies, even in data-sparse areas, when a feature-modeled field is used as a first guess; (3) feature models are an effective means of using a knowledge of the oceanography of fronts and eddies to supplement sparse observations and to infer subsurface thermal structure from surface observations.

The following recommendations are made: (1) A feature-modeled field is only as good as the front and eddy map that is used to construct it. The accuracy and timeliness of front and eddy maps ought to be improved through the development of new technologies and the more effective application of existing technologies. (2) Feature models need to be developed for other areas, such as the Northeast Pacific, and other oceanic phenomena, such as upwelling. (3) Methods need to be developed that will use observations to tune or tailor feature models to specific situations.

VIII. Summary

When doing an objective analysis of ocean temperature data, it is desirable to have as realistic a first-guess field as possible because the analysis will resemble the first guess in data-poor areas. Feature modeling can be used to construct a first-guess field that is more realistic than climatology alone. Feature modeling involves placing schematic thermal representations of fronts and eddies, i.e., feature models, along the paths and positions indicated on a front and eddy map and using a water-mass-based climatology to describe the associated water masses. The result is a tight gradient meandering along the identified frontal path that closely matches observed thermal structure. At each identified eddy location is a typical eddy whose thermal structure is a simple function of eddy rotation rate and radius. In contrast, fronts in a static climatology are generally broad, weak and without meanders, and mesoscale eddies have been averaged out.

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Ocean acoustics are crucial to modern naval operations. Acoustics constantly change due to the variability in space and in time of the ocean thermal structure. Thus, a thermal analysis system that transforms irregularly sampled data from disparate sources into an analysis of the ocean thermal structure is of increasing importance. In a data-sparse environment such as the ocean, the key to obtaining realistic but cost-effective analyses is the use of all available data sources, as well as the most powerful data assimilation techniques.

Feature modeling is a powerful means of supplementing the limited in situ and remotely sensed data with our understanding of the oceanography of mesoscale ocean features. Initially, the data are used to map the location of mesoscale fronts and eddies. Schematic descriptions of the thermal structure of these features, called feature models, are subsequently used to represent them in the first-guess thermal field. In data-sparse areas, features that would otherwise be poorly resolved in the analysis are instead represented by these schematic models.

The Naval Ocean Research and Development Activity has developed feature models for the Gulf Stream front and eddies, as well as an algorithm for the incorporation of the models into the first-guess field. The models were evaluated at the Fleet Numerical Oceanography Center within the Optimum Thermal Interpolation System (OTIS) framework. Subsurface thermal fields constructed via these feature models agree well with observed fields and are substantially more realistic than analyses produced using the current regional operational system, the Expanded Ocean Thermal Structure (EOTS) analysis. Because of the power of feature modeling, feature modeling has considerable relevance to other Navy-funded work in ocean modeling and remote sensing.

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